

Proper Motions in Kapteyn Selected Area 103: A Preliminary Orbit for the Virgo Stellar Stream

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ABSTRACT

We present absolute proper motions in Kapteyn Selected Area (SA) 103. This field is located 7° west of the center of the Virgo Stellar Stream (VSS, Duffau et al. 2006), and has a well-defined main sequence representing the stream. In SA 103, we identify one RR Lyrae star as a member of the VSS, according to its metallicity, radial velocity, and distance. VSS candidate turnoff and subgiant stars have proper motions consistent with that of the RR Lyrae star. The 3D velocity data imply an orbit with a pericenter of ~ 11 kpc and an apocenter of ~ 90 kpc. Thus, the VSS comprises tidal debris found near the pericenter of a highly destructive orbit. Examining the six globular clusters at distances larger than 50 kpc from the Galactic center, and the proposed orbit of the VSS, we find one tentative association, NGC 2419. We speculate that NGC 2419 is possibly the nucleus of a disrupted system of which the VSS is a part.

Subject headings: Galaxy: structure — Galaxy: kinematics and dynamics — Galaxy: halo

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1. Introduction

It is now recognized that numerous stellar streams inhabit the Galactic halo (e.g., Newberg et al. 2002; Belokurov et al. 2006; Grillmair et al. 2006, based on the Sloan Digital Sky Survey - SDSS, and Vivas & Zinn 2006 based on the Quasar Equatorial Survey Survey Team - QUEST, to name only a few). This newly discovered abundance of substructure has generated much attention, as it qualitatively fits into the framework of a Λ cold dark matter cosmology that envisions the formation of the Galaxy via hierarchical merging. However, the lack of available full phase-space descriptions of the substructure limits our ability to properly model and quantify the merging history of our Galaxy. It is certain that the formation and dynamical evolution of tidal streams and overdensities is strongly affected by the Galactic potential, in addition to the characteristics of the stream’s progenitor (e.g., Johnston et al. 1999; Murali & Dubinski 1999). These effects cannot be properly modeled simply with projected positions on the sky, distances, and in some cases radial velocities. Moreover, these tidal features cannot be properly disentangled in regions of the sky where they overlap in projection. One such example is the region of the Virgo stellar OverDensity (VOD). This region, first noted by Newberg et al. (2002), and Vivas and Zinn (2003), covers a large region on the sky ($\sim 1000^\circ$), as recently shown by Juric et al. (2008). While a rather low surface-brightness feature (< 32.5 mag arcsec $^{-2}$), the VOD itself appears to have substructure seen in surface density as well as in radial-velocity space (Duffau et al. 2006 - D06, Newberg et al. 2007 - N07; Vivas et al. 2008 - V08; Keller et al. 2008 - K08; Keller et al. 2009; Prior et al. 2009 - P09). The best-characterized stream in the VOD is known as the Virgo Stellar Stream (VSS, a.k.a. the 12.4-hour clump of Vivas & Zinn 2003) and it is the subject of this paper. The VOD remains a complex region, where stars from both the leading and trailing tidal tails of Sgr may be found as noted by Kundu et al. (2002), Martínez-Delgado et al. (2007), P09.

In this paper we present absolute proper motions in Kapteyn Selected Area (SA) 103, located at (R.A., Dec.) = $(178.8^\circ, -0.6^\circ)$ and $(l, b) = (264.6^\circ, 59.2^\circ)$. The center of the VSS is at (R.A., Dec.) = $(186^\circ, -1^\circ)$; it extends in R.A. from 175° to 200° (D06), while in Dec. it has been shown to extend from 0° to -15° (P09). SA 103 is thus $\sim 7^\circ$ west of the VSS center as defined by D06. In this field, we were able to identify one RR Lyrae star as a VSS member for which the absolute proper motion is measured. This allows us to obtain a preliminary orbit for the VSS.

2. Data and Results

SA 103 is one field of ~ 50 from the proper-motion survey described by Casetti-Dinescu et al. (2006, CD06). In CD06 all details concerning the reduction process and the derivation of proper motions are presented. Here, we only briefly mention the basics of this survey. Each field covers $40' \times 40'$, and makes use of photographic plates taken at three different epochs. The modern epoch consists of plates taken between 1996 and 1998 with the Las Campanas du Pont 2.5m telescope, the intermediate epoch consists of Palomar Observatory Sky Survey plates (POSS-I) taken in the early fifties with the Oschin Schmidt 1.2m telescope, and the old epoch consists of plates taken between 1909 and 1911 with the Mount Wilson 1.5m telescope. The modern and old plates were measured with the Yale PDS microdensitometer. For the POSS-I plates we have used scans done by both the Space Telescope Institute (the Digitized Sky Survey) and the US Naval Observatory. For SA 103 we have used two du Pont plates two overlapping POSS-I fields, and one 60-inch Mt. Wilson plate. The region of SA 103 has complete SDSS DR7 (Abazajian et al. 2009) coverage. Thus, by comparing with the DR7 data, our proper-motion catalog in SA 103 is 86% complete at $g = 20.0$, and becomes 15% complete at $g = 21.0$. The limiting magnitude for objects that have over a 80-year baseline (i.e., those that were measured on the Mt. Wilson plates) is $g \sim 20.0$, with $\sim 90\%$ completeness at $g = 17.0$. For objects that are well-measured (i.e., $g \leq 18$), we obtain proper-motion errors of $\sim 1 \text{ mas yr}^{-1}$, as shown in CD06 and Casetti-Dinescu et al. (2008). All proper-motion units in this paper are mas yr^{-1} .

We have searched the Vivas et al. catalogs to find matches with stars in our SA 103 field. We have identified one RR Lyrae star – RR 167, classified as Bailey type ab, in the Vivas et al. catalogs in our field. RR 167 ((R.A., Dec.) = $(178.893^\circ, -0.600^\circ)$) is located near the center of our field and, with an average magnitude $V = 16.77$, it is a well-measured star, with the proper motion derived from thirteen position measurements across 86 years. The same star is also listed in the K08 catalog. Vivas et al. (2006) determine a heliocentric distance of 16.9 kpc, while K08 a distance of 18.3 kpc. Both studies estimate a 7% uncertainty in the distances, therefore the distances agree within uncertainties. No radial velocity (RV) or metallicity information is provided for RR 167 in subsequent studies that focus on the VSS. We have thus searched the SDSS DR7 data for spectroscopic observations in SA 103, and fortunately we have found that RR 167 had two spectra taken near minimum light (phase 0.70 and 0.75). The phases of the spectroscopic observations were calculated using the QUEST ephemeris which, for this star, was based on 30 epochs in the light curve. From these spectra, the systemic heliocentric radial velocity of the star was determined to be $242.7 \pm 14.0 \text{ km s}^{-1}$ using the procedure described in V08, which consists of fitting the radial velocity curve of the well studied RR Lyrae star X Arietis. The 2 SDSS radial velocities for RR 167 fit quite well the curve of X Arietis (rms of the fit = 3 km s^{-1}). The quoted error

however includes the uncertainties due to possible variations from star to star in the slope of the radial velocity curve and the phase when the systemic velocity occurs. In the Galactic rest frame the velocity is $V_{gsr} = 134.3 \pm 14.0 \text{ km s}^{-1}$. The metallicity was determined from the CaII K and H δ , H γ , and H β equivalent width using the procedure outlined in Layden (1994). The metallicity values derived from the two spectra are -1.79 ± 0.22 and -1.84 ± 0.21 . Based on this metallicity (-1.8 ± 0.2) we have re-estimated the distance to RR 167, and we obtain $17.0 \pm 0.9 \text{ kpc}$, which is the value that we use for the orbit determination. The properties of stars in the VSS as determined by previous studies are summarized below. D06 find a somewhat smaller mean velocity than subsequent studies, $V_{gsr} \sim 99 \text{ km s}^{-1}$ from a sample of 6 RR Lyrae and blue horizontal branch (BHB) stars¹. The metallicity determined by D06 is $[\text{Fe}/\text{H}] = -1.86 \pm 0.15$, with the VSS having a significant metallicity spread ($\sim 0.4 \text{ dex}$) intrinsic to the structure. N07 obtain $V_{gsr} = 130 \pm 10 \text{ km s}^{-1}$ from data on F-type turnoff star, while P09 obtain $V_{gsr} = 127 \pm 10 \text{ km s}^{-1}$ (average of four RR Lyrae stars), and $[\text{Fe}/\text{H}] = -1.72$ and -2.15 for two stars with available metallicity estimates. The distance to stars in the VSS sampled by D06 is 19 kpc, while N07 estimate a distance of 18 kpc. From the more recent study by V08, the distance to VSS ranges between 12 and 19 kpc. Thus, the estimated distance, RV, and metallicity of RR 167 make it a very likely member of the VSS.

Figure 1 shows the formal proper-motion errors as a function of g magnitude for stars in SA 103. RR 167 (filled circle) has formal errors within the range for stars at that particular magnitude. The proper-motion zero-point for an inertial reference frame is determined from the measurement of background galaxies as classified by SDSS. We use 302 galaxies with measured proper motions less than 20 mas yr^{-1} and that had at least four positional measurements. To determine their mean and dispersion, we apply the probability-plot method (Hamaker 1978) using the inner 80% of the proper-motion distribution. In our data we also have four rather faint QSOs (as identified from SDSS DR5, see Schneider et al. 2007), $g = 18.8 - 19.5$. The galaxies and QSOs determinations agree within errors. We obtain a final zero point from the mean proper motions of the galaxies and the QSOs, weighted by their formal errors. Our final zero point is $\mu_{\alpha} \cos \delta = 3.69 \pm 0.27 \text{ mas yr}^{-1}$ and $\mu_{\delta} = 2.62 \pm 0.28 \text{ mas yr}^{-1}$. Figure 2 shows absolute proper-motion diagrams (i.e., with the zero point applied such that galaxies are centered on 0,0) for stars (left panel) and galaxies (right panel). RR 167 is the filled circle. The open circles in the galaxies' diagram are the QSOs. The absolute proper motion of RR 167 is $\mu_{\alpha} \cos \delta = -4.85 \pm 0.85 \text{ mas yr}^{-1}$ and $\mu_{\delta} = 0.28 \pm 0.85 \text{ mas yr}^{-1}$. Here, the error is determined by adopting the median value for the error of a star with the magnitude of RR 167, as seen in Fig. 1 (i.e., 0.8 mas yr^{-1}), and adding in

¹However, a recent revision of the QUEST velocities gives a mean velocity for the VSS of 126 km s^{-1} , in perfect agreement with the other works (Duffau 2008)

quadrature the error in the zero point determination. This is done to avoid underestimating the error by using the value formally obtained from the fit of positions as a function of time. Clearly, RR 167 has a high proper motion, detected at the 5.7σ level. Such a large proper motion for an object at ~ 17 kpc implies a very energetic orbit (see next Section). The proper motion corrected for the reflex solar motion is $\mu_\alpha \cos \delta = -3.50 \pm 0.85$ mas yr $^{-1}$ and $\mu_\delta = 2.33 \pm 0.85$ mas yr $^{-1}$.

To further explore the presence of VSS debris in SA 103 we present observed color-magnitude diagrams (CMDs) and proper-motion diagrams, and compare with their Besancon-model (Robin et al. 2003) equivalents. The top panels of Figure 3 show the CMDs of an area centered on SA 103, and covering our $40' \times 40'$ area. The left panel shows all stars from DR7, the middle panel shows the Besancon model data, and the right the DR7 data for stars with available proper-motion measurements. The location of RR 167 is highlighted with a filled circle. The dashed line indicates the approximate limiting magnitude of our proper-motion data. The DR7 data exhibit a distinct main-sequence like overdensity, as well as a mild enhancement at the location of a corresponding horizontal branch. The SA 103 region has also been analyzed by P09, who examined SDSS data as well as their own V, R starcounts, and found a clear stellar excess compared to the Besancon-model starcounts in the turn-off region of the CMD (their Figs. 13 and 14 - top panels). They also compared the region in SA 103 to other two regions, of which one, at R.A. = 218° , shows no stellar excess compared to the Besancon model. To better characterize the stellar overdensity in SA 103, we overlay the fiducial sequence of globular cluster M 53 in Fig. 3. The fiducial sequence is constructed from the DR7 data, and is represented with a grey line in the top-left panel. M 53 has a metallicity $[\text{Fe}/\text{H}] = -1.99$, and is located at a distance of 17.8 kpc (Harris 1996). Thus, it is representative of the VSS population. The reddening in SA 103 is $E(\text{B}-\text{V}) = 0.026$, while at the location of M 53, it is $E(\text{B}-\text{V}) = 0.021$ (Schlegel et al. 1998). Therefore, only small adjustments due to reddening had to be made to the fiducial sequence of M 53 in order to align it with the VSS. We chose not to adjust the distance modulus, since our distance to RR 167 agrees with that of M 53 within errors. Figure 3 shows that the VSS closely follows M 53's fiducial sequence; it is slightly redder, and there are no BHB stars. This indicates that the VSS is slightly more metal rich than M 53, in agreement with the spectroscopic determinations that give a 0.2dex difference.

The next step is to identify more likely VSS candidates in our proper-motion field. In the well-measured regime (~ 1 mas yr $^{-1}$, $g < 18.0$) we expect very few stars. Both K08 and Vivas et al. (2004) have surveyed this region, and found only one RR Lyrae star which is in keeping with our expectations from the proper-motion field. There could be several more red horizontal-branch stars, as the CMD appears to indicate, however without RV information it is difficult to confidently distinguish them from field stars. Likewise, we expect very few

giants. From M 53’s DR7 CMD (within a 10-arcmin radius from the cluster center) we obtain a ratio of about three red giant-branch stars (approximately from the tip to the subgiant region) for each horizontal-branch star. Thus, even along the giant branch we can’t expect more than about ten VSS stars. Lacking RV information, the giant branch VSS stars have the additional problem of being virtually impossible to distinguish from the ~ 60 field stars that inhabit the same band as the M 53 giant branch. The highest contrast between the VSS and the Galactic field where proper-motions are available is the subgiant and turnoff region, which is also where proper-motion errors are the largest. Nevertheless, we have selected stars in this region to check the overall proper-motion distribution, and compare it to that predicted by the Besancon model. The stars are selected within the rectangular box highlighted in the CMDs of Fig. 3. Our data include 93 stars, while the Besancon model predicts ~ 66 stars. Note that while the Besancon sample is complete, the data are not (at $g = 20$, completeness is 85%). The proper-motion distribution of our data is shown in the bottom-left panel of Fig. 3, where formal error bars are included for each star. The middle panel shows the proper-motion density contour map of our data, while the left panel shows that of the Besancon data convolved with 4 mas yr $^{-1}$ error. Reassuringly, in the observed data the region of peak density includes RR 167. The Besancon proper-motion distribution shows a density peak at a different location than that of RR 167; this peak is also lower than that of the observed distribution, which reflects the stellar overdensity found in this area.

3. A Preliminary Orbit Determination for the VSS

The velocity components in cylindrical coordinates (Π, Θ, W) are calculated using the RV, distance and proper motion listed above for RR 167. Using the Dehnen et al. (1998) peculiar velocity of the Sun, at $R_0 = 8$ kpc, and $\Theta_0 = 220$ km s $^{-1}$, we obtain $(\Pi, \Theta, W) = (253 \pm 65, 221 \pm 67, 142 \pm 37)$ km s $^{-1}$. We have integrated the orbit in the Johnston et al. (1995) Galactic potential, following the procedure described in Dinescu et al. (1999) to estimate uncertainties in the orbital parameters. We obtain an orbit with a pericentric radius of 11 ± 1 kpc, an apocentric radius of 89^{+52}_{-32} kpc, and an eccentricity of 0.78 ± 0.06 . The orbital inclination is $58^\circ \pm 5^\circ$, derived as $90^\circ - \sin^{-1}(L_z/L)$, where L_z is the angular momentum along the direction perpendicular to the Galactic disk, and L is the total angular momentum. The radial orbital period is $1.2^{+0.6}_{-0.4}$ Gyr. These orbital elements rule out any association of the VSS with Sgr’s orbit (e.g., Dinescu et al. 2000; Dinescu et al. 2005). In particular, examination of the three integrals of motion for the orbits of Sgr and the VSS shows that while the total orbital energy and angular momentum are not determined with sufficient precision for the VSS to safely rule out its association with Sgr, the L_z differs at the 2.2σ level. The current location of the RR 167 is ~ 17 kpc from the Galactic center. Thus,

the orbit obtained indicates that the stars in the VSS are near pericenter. Interestingly, the smallest distance for stars in the VSS is estimated to be 12 kpc (V08). Using this distance at the sky location of RR 167, we obtain a Galactocentric distance of 14 kpc, which is in reasonable agreement with our determination for the pericentric radius of the orbit. Although the uncertainty in the apocentric radius is rather large, owing to distance and proper-motion errors, it is apparent that the orbit is very eccentric and thus rather destructive for the parent satellite. Disruption models of satellites on eccentric orbits indicate that tidal debris piles up preferentially at the turning points of an orbit (e.g., the disruption of Sgr: Law et al. 2005). Therefore, the VSS structure is consistent with a pericentric density enhancement of a disrupted satellite on a highly eccentric orbit. While the orbit is somewhat uncertain, it is a highly energetic one, with an apocenter beyond 50 kpc. We show this orbit in Figure 4, along with that of Sgr for comparison. Since there are only six globular clusters beyond a Galactocentric radius of 50 kpc, we searched for positional coincidence between the orbit of the VSS and distant clusters. There is only one cluster that can be associated with this orbit, namely NGC 2419 which is 13 kpc away from the closest point in the VSS orbit, integrated back in time for 5 Gyrs. NGC 2419 is a well-known massive cluster with a low metallicity ($[\text{Fe}/\text{H}] = -2.12$), and a very extended BHB. As such, its properties fit the idea that massive, extended BHB clusters are the nuclei of disrupted dwarf galaxies (Lee et al. 2007). Cluster NGC 2419 ($(l, b) = (180.4^\circ, 25.2^\circ)$) has been tentatively associated with debris from Sgr by Newberg et al. (2003). This association is based on the proximity of NGC 2419 to Sgr’s orbital plane, and on the finding of an overdensity of A-type stars (assumed to be BHB stars) at a galactocentric distance of ~ 90 kpc that lie near Sgr’s orbital plane toward the direction of NGC 2419 (Newberg et al. 2003). Disruption models of Sgr (Law et al. 2005) show that debris from Sgr can be found in the region and at the galactocentric distance of NGC 2419, as part of the trailing tail, thus suggesting that the cluster and the A-type star overdensity could belong to Sgr. The low radial velocity of NGC 2419, $V_{gsr} = -27 \text{ km s}^{-1}$ (Harris 1996) indicates that the cluster is at a turning point in its orbit (in this case the apocenter), which can be equally implied by the membership to Sgr and VSS (Fig. 4). Since NGC 2419 is in the Anticenter direction, only its transverse velocity can establish whether it is associated to any of these two streams.

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Facilities: SDSS.

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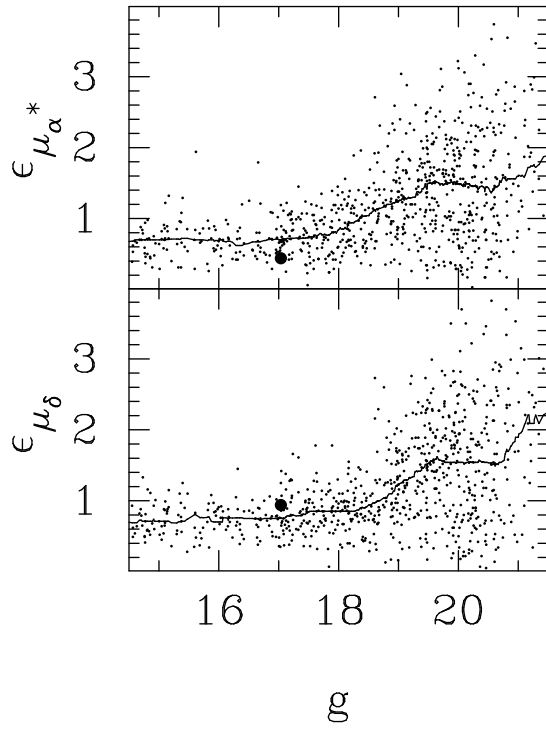


Fig. 1.— Proper-motion errors in each coordinate as a function of magnitude for stars. The line represents the moving median of the sample. The filled circle is RR 167. Here, $\mu_{\alpha}^* = \mu_{\alpha} \cos \delta$.

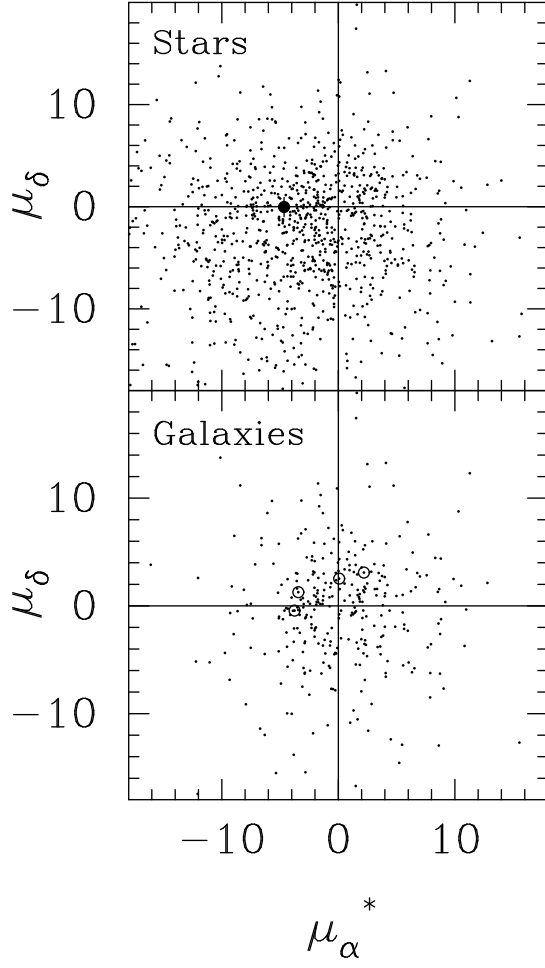


Fig. 2.— Absolute proper-motion diagrams for stars (left) and galaxies (right). The filled circle is RR 167. The open circles in the right panel show the four quasars that were measured in this area.

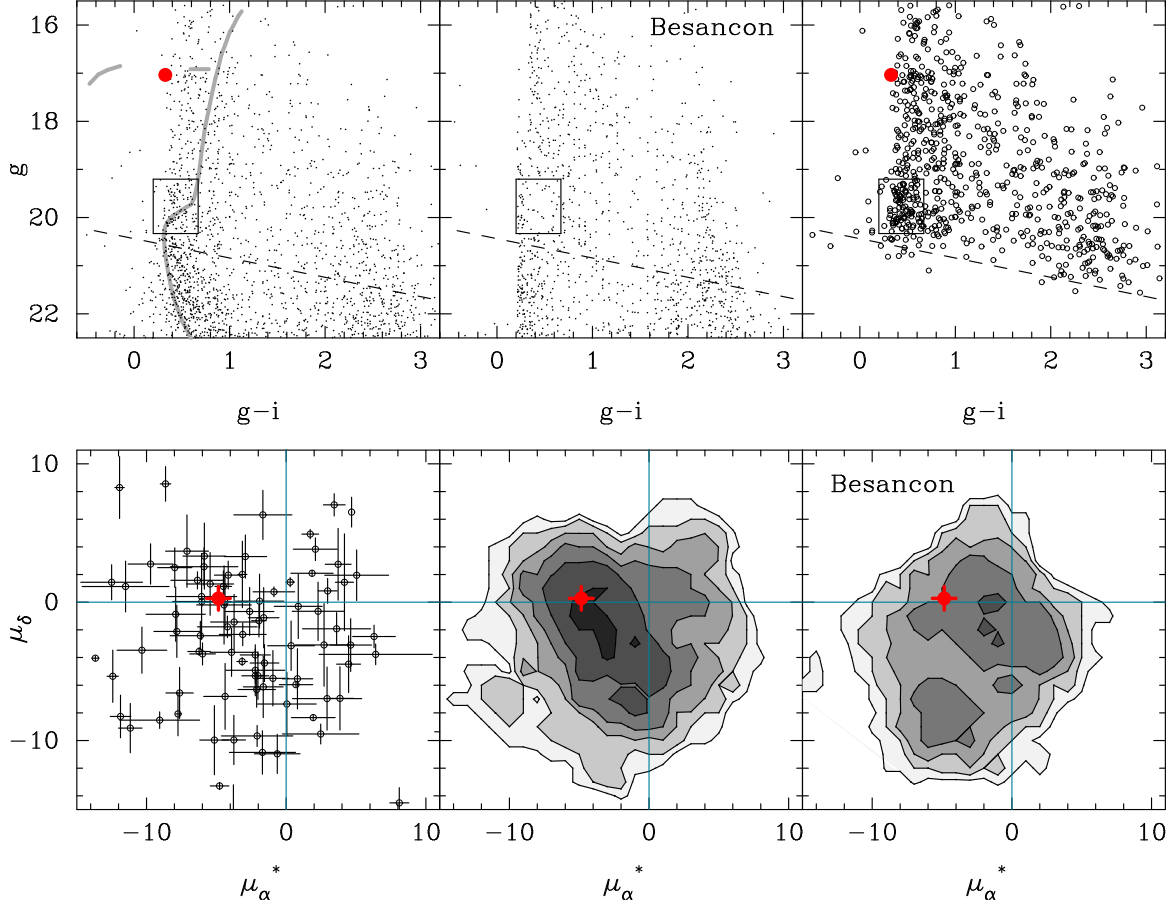


Fig. 3.— The top panels show CMDs in SA 103: all SDSS data (left), Besancon model (middle) and SDSS data for star with proper motions (right). The gray line in the left panel shows the fiducial sequence of globular cluster M 53. The red symbol represents RR 167, the dashed line indicates the faint limit of the proper-motion data. The rectangular box shows the CMD-selection of stars for which proper motions are displayed in the bottom panels. The bottom panels show the proper-motion distributions: our data (left), our data mapped with logarithmic contours of the proper-motion density distribution (middle), and the Besancon model distribution (right) with same contours as for our data.

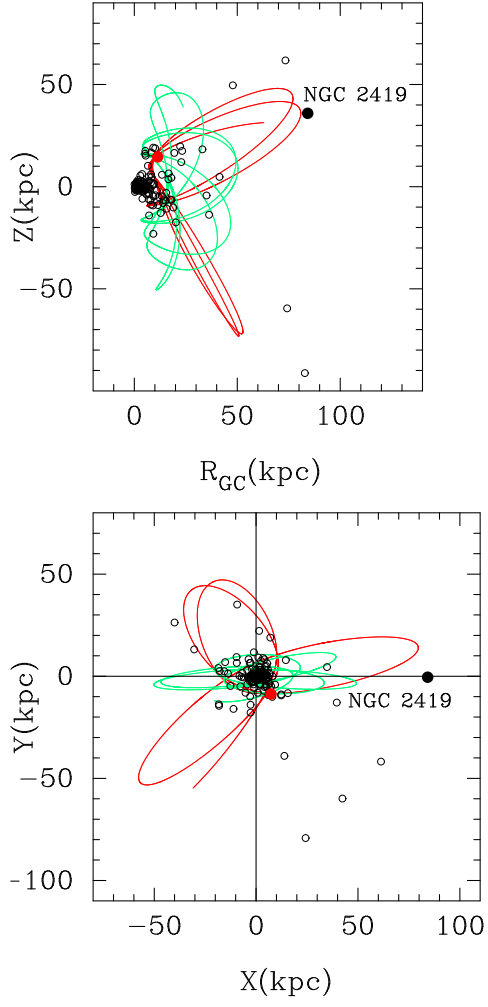


Fig. 4.— Orbits of the VSS (red) and Sgr (green), seen in R-Z projection (left) and in the disk plane (right) integrated back in time for 5 Gyr. Open circles show the globular clusters. NGC 2419, tentatively associated with the VSS is labeled. The Sun is at $(X,Y,Z) = (8,0,0)$ kpc. The current location of RR 167 is marked with a red filled circle.